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ENERGY, WHAT WE NEED AND WHAT WE CAN

Climate emergency and sustainable growth: a way forward for economics as a discipline

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Abstract

Addressing the economics of climate change requires a systemic approach, integrating insights from the natural and social sciences. In the face of environmental catastrophes that are causing massive migration and invaluable losses, economists are finding themselves ill-equipped to play their part. The climate crisis is undermining the basis of traditional economic growth models and providing a new impetus to revise economic theory. This paper explores how the economic world operates as an open system, in which uncertainty and multiple potential processes dominate economic events. It proposes that the coherent set of concepts and tools introduced by quantum theory is well suited to interpreting the dynamics of economic processes. Ultimately, the climate crisis is forcing us to question the primacy of market laws, which are ubiquitous in economic theory. The inevitable outcome of this trajectory should be the cross-fertilisation between different perspectives from the East, West, and “Global South”.

Keywords The climate crisis · Economic uncertainty · Quantum foundations

> I have embarked on a journey as dangerous as any other on the basis of a simple conjecture: I can already see the promontories of new lands. May the joy of reaching them be reserved for those who have the courage to continue the search.” (Kant 1755)

1 Introduction

1.1 Transitions

In just a few decades, the global system has undergone profound transformations in the natural, environmental, scientific and socio-economic dimensions. Tackling climate change requires a systemic approach that integrates insights from physics, economics, history, chemistry, geology, geography, volcanology and information technology.

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Economics itself should return to a multidimensional perspective. Economists must understand and manage the ongoing dynamics, addressing critical issues such as the economic impact of the planet's energy imbalance on the most vulnerable regions and social groups. This covers a broad range of factors, from analysing the radiative forcing of atmospheric warming to assessing the costs of a green transition, from implementing carbon emission reduction strategies to developing adaptation policies. Economists are also tasked with analysing the implications of the energy transition on the labour market and the emerging business opportunities. It is essential that they leverage the tools and insights provided by scientific research, including the computational power of quantum computers to process the infinite array of future scenarios.

The scientific community has issued a definitive warning: immediate global action is imperative. Climate change has the potential to serve as a unifying factor for global objectives and the necessary coordination of economic policies. The damage caused by climate change is already substantial. In 2023 alone, quantifiable losses have been projected to reach USD 357 billion, with private insurance covering USD 110 billion and public insurance institutions covering a mere USD 13 billion. As a result, 66% of the damage has remained uncovered (Gallagher Re, 2024). In 2024 more than 600 extreme weather events, including 148 classified as “unprecedented”, displaced 824.000 people and led to 1700 deaths, according to the World Meteorological Organization (WMO). They caused losses of USD 320 billion, with USD 140 billion being insured.

Most important is to account for the cost of inaction.

Regions recently hit hardest by extreme weather include China, where floods have occurred; the Philippines and Taiwan, affected by damaging hurricanes; Mexico and India, both impacted by destructive cyclones; and Myanmar, Bangladesh, Oceania and New Zealand, experiencing floods and droughts. In South America and Europe, storms caused significant damage, particularly in France, Italy, Greece and Spain. Additionally, heat and drought have heavily affected Canada, while the USA has faced hurricanes in Florida, cyclones and fires in Hawaii and droughts that have severely reduced agricultural yields. Throughout 2024, global temperatures always exceeded the 1.5 °C threshold compared to pre-industrial levels—a critical limit widely regarded as potentially leading to irreversible damage (Swiss RE Institute 2021).

Figure 1 highlights the rapid acceleration of this warming trend and the imminent approach of the points of no return (Table 1).

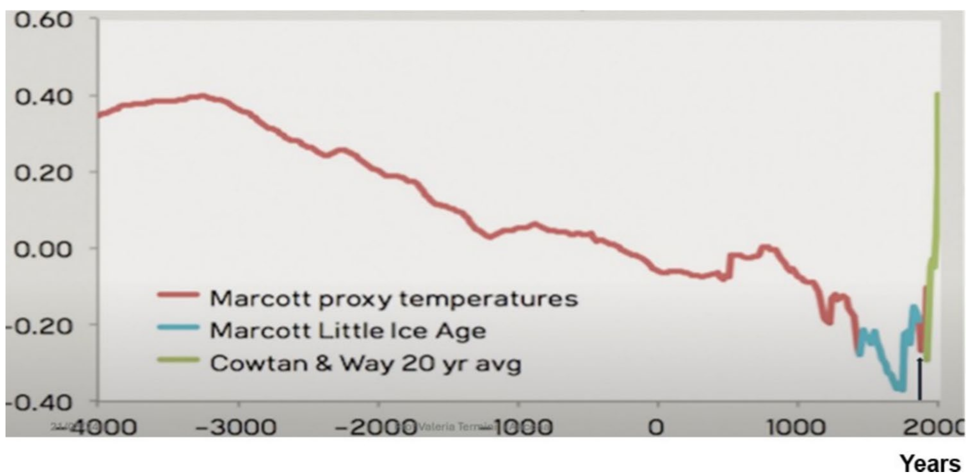

Fig. 1 Rate of global warming (°C). In the fifteenth century, the Little Ice Age occurred; after 1750 the Industrial Revolution triggered rapid warming. Prior to the Industrial Revolution, the planet maintained a relatively stable decreasing average temperature, as estimated by scientists from the Intergovernmental Panel on Climate Change (IPCC). These figures, while approximate due to the time span (4000 years), show this stability. The green line, which begins around 1750, marks the rapid temperature increase following the Little Ice Age and the Industrial Revolution. *Source*: *Observed ClimateVariationsand Change*”, *in IPCCEarth’smostrecent4000-year* period (2021 marked the release of the final instalment of the Intergovernmental Panel on Climate Change’s (IPCC) Sixth Assessment Report (AR6) drawing on the findings of 234 scientists on the physical science of climate change, 270 scientists on impacts, adaptation and vulnerability to climate change, and 278 scientists on climate change mitigation, this IPCC synthesis report provides the most comprehensive, best available scientific assessment of climate change.)

Table 1 Projected impact of global temperature increase on GDP (%) to 2050 by region

Region	Increase < 2 °C	Increase of 2 °C	Increase of 2.6 °C	Increase of 3.2 °C
World	−4.2	−11	−13.9	−18.1
OCSE	−3.1	−7.6	−8.1	−10.6
North America	−3.1	−6.9	−7.4	−9.5
South America	−4.1	−10.8	−13	−17
Europe	−2.8	−7.7	−8	−10.5
Middle East and Africa	−4.7	−14	−21.5	−27.6
Asia	−5.5	−14.9	−20.4	−26.5
Advanced Asian nations	−3.3	−9.5	−11.7	−15.4
ASEAN	−4.2	−17	−29	−37.4
Oceania	−4.3	−11.2	−12.3	−16.3

Source: Swiss Re Institute—The economics of climate change: no action is not an option, April 2021: https://www.swissre.com/dam/jcr:e73ee7c3-7f83-4c17-a2b8-8ef23a8d3312/swiss-re-institute-expertise-publication-economics-of-climate-change.pdf

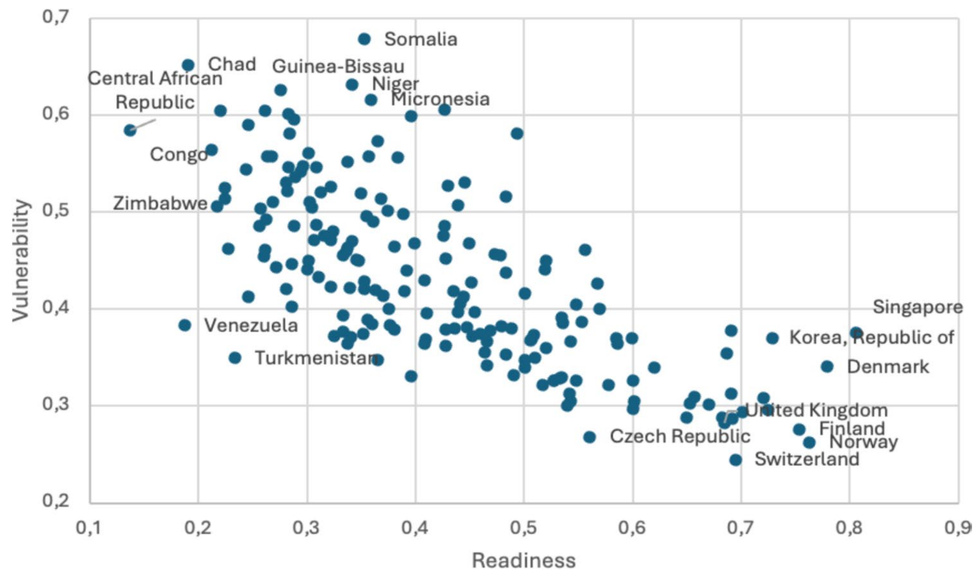

Fig. 2 Vulnerability and readiness to climate disasters. On average, African countries are losing 2–5% of gross domestic product (GDP). "In sub-Saharan Africa, the cost of adaptation is estimated to be between US$ 30–50 billion annually over the next decade, or 2–3% of the region's Gross Domestic Product"; this is written in the WMO State of the Climate in Africa 2023 report. Furthermore, climate extremes including floods and droughts had a major impact on food security. *Source*: compiled from data https://gain.nd.edu/our-work/country-index/matrix/ of the *Notre Dame Global Adaptation Initiative*. Italy 2023: Vulnerability 0.34 Readiness 0.51

However, the key issues in terms of impacts are not simply or mainly about global warming as such. Understanding these changes requires specific analysis of how climate will be affected regionally, as Stern observes (2013). "Africa bears an increasingly heavy burden from climate change and disproportionately high costs for essential climate adaptation", according to the 2024 report of the World Meteorological Organization (WMO 2024).[1] The highest temperature anomalies were recorded across northwestern Africa, especially in Morocco, Mauritania and northwest Algeria.[2]

The following figures offer a synthetic view of regional climate impacts (Figs. 2, 3).

[1] WMO, the African Union Commission, United Nations Economic Commission for Africa and the African Ministerial Conference on Meteorology released the report at the 12th Climate Change for Development in Africa (CCDA) Conference in Abidjan, Ivory Coast, on 2 September 2024. Regions with a marked rainfall deficit included the western part of North and Northwestern Africa, the Horn of Africa, Southern Africa including Zambia, Zimbabwe, Botswana, and Namibia; moreover, Madagascar, central Sudan, northern Ethiopia and Uganda. Libya was hit by flooding following the Mediterranean cyclone 'Storm Daniel' in September; the same crisis was in Mozambique and Malawi, the border between Rwanda and the Democratic Republic of Congo, with Niger, Benin, Ghana and Nigeria most heavily impacted. On the other hand, severe drought has struck Morocco, Algeria, Tunisia, Nigeria, Cameroon, Ethiopia, Madagascar, Angola, Zambia, Zimbabwe and Democratic Republic of Congo.

[2] Tunis reached a record of 49.0 °C and Agadir (Morocco) reached a new maximum temperature of 50.4 °C (WMO 2024). https://wmo.int/

Finally, the occurrence of seemingly unrelated traumatic events—pandemics, climate-induced mass migrations, wars and financial crises—underscores the West's loss of control and the inherent challenges of re-establishing multipolar balance in the wake of the declining political and economic leadership of the USA. Yet, at the same time, the projection and application of radical scientific innovations have reshaped the organisation of life, offering the potential for leapfrogging development in newly industrialised countries, as A. Ghosh has insightfully observed in India (2017).

The confluence of these disparate factors marks a rupture in the global order established in the previous century, signalling shifts in the long-term fault lines of history that the theory must take into account.

Towards what?

In a nutshell, the new millennium has been defined by three major transitions: a "*hegemonic transition*" (as described by Arrighi and Silver 2024), an "*ecological transition*",[3] and an "*economic transition*" (Acemoglou and Robinson 2012, 2023) driven by the energy and digital revolutions. As history shows, hegemonic transitions are often fraught with severe conflicts, persisting until new global balances are achieved through international agreements. Today's era is marked by planetary disorder, with the proliferation of conflicts made dramatic by the widespread

[3] On the energy transition, I would refer to Termini (2021, 2024), Masulli and Termini (2019).

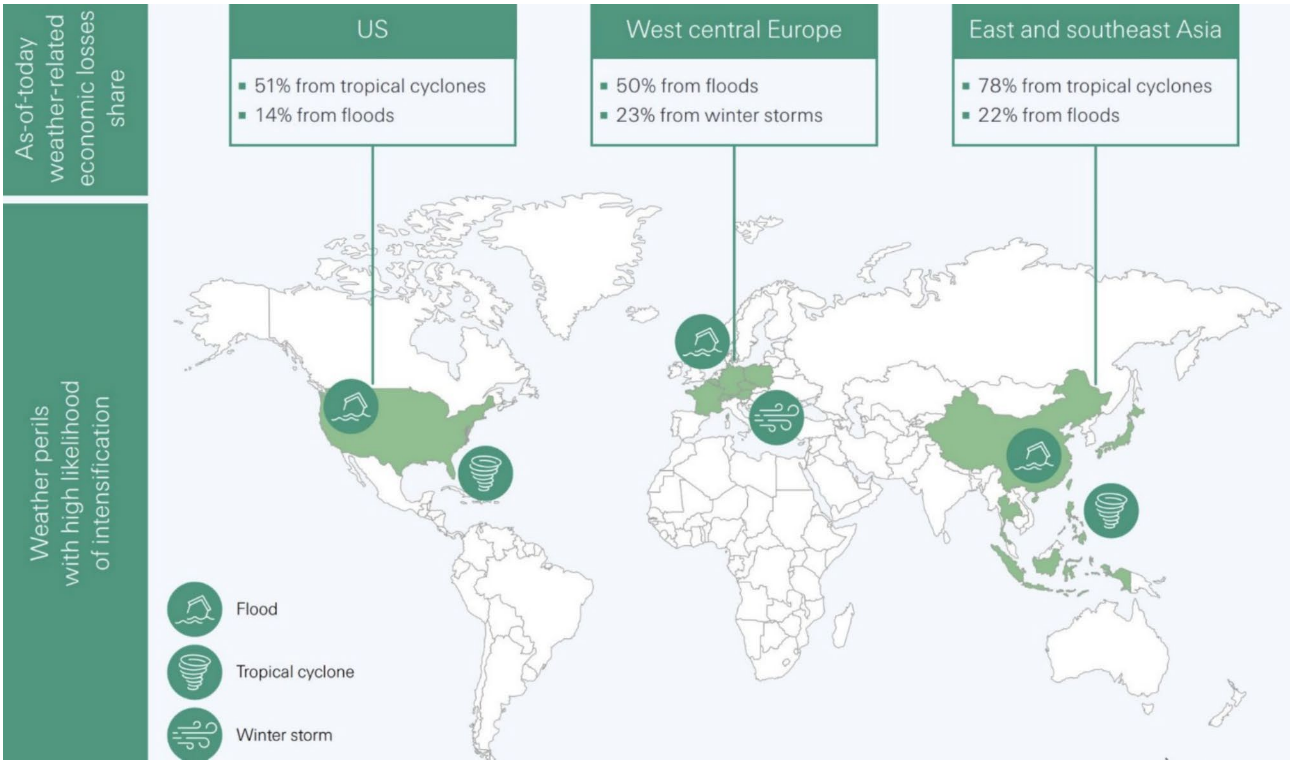

Fig. 3 Regions with the highest probability of an increase in the likelihood of losses from climate-related risks. Economic losses from natural catastrophes are expected to increase due to climate change. Primary drivers of these increased losses are severe weather events such as hurricanes, severe thunderstorms and floods. According to Swiss Re, the regions with the highest probability of increased losses from climate-related risks are the USA and the Philippines. Additionally, fast-growing Asian economies such as Thailand, China and India are also identified as highly vulnerable. Swiss Re is a leading player in the global reinsurance market. *Source*: Swiss Re Institute

availability of different nuclear weapons. While historical analysis offers valuable insights into these developments, economic analysis and policy remain inadequate. They are limited by theoretical foundations developed in the early twentieth century.

1.2 Economics must change: the economic discipline for transition

A new perspective is urgently needed. However, the purpose of this paper is to show why contemporary economic theories lack the tools required to understand and regulate the unexpected dynamics of this new era, as well as to address the uncertain and far-reaching economic impacts of emerging scientific and technological revolutions. As a result, economists find themselves ill-equipped to interpret their role amid an environmental catastrophe that is eroding the foundations of traditional growth models. My immersion in energy and climate issues led me to realise that the dominant economic vision and growth models are inflicting irreversible harm on the planet, its creatures and even humanity. Indeed, it is on the verge of destroying it.

This brings me to reflect on the challenges economics as a discipline faces in addressing the climate crisis with a coherent set of concepts and relationships, and to explore potential frameworks to understand the rupture occurring in today's economic reality. In the 1930s, Keynes remarked that "it is ideas that shape the world." In light of the radical and accelerating changes we face, it is clear that economists' interpretative models must change. This is especially evident when examining energy crises, climate risks and the ecological and digital transitions.

The argument introduced here rests on two key pillars. Firstly, the *methodological tenets* of mainstream economic theory, which is largely rooted in the neo-classical marginalist tradition is not helpful; secondly, the *demise of the primacy of the market* in shaping economic policy is a fact. I will separately consider the two issues.

Firstly, the failure of contemporary economic theories to interpret current events can be traced to their methodological foundations, which remain grounded on the worldview of the nineteen century, when the economic theory borrowed the methods and analytical tools of classical physics. The methodological contrast between Keynes and Tinbergen anticipated this difficulty. The application of econometric models in the twenty century has then helped to strengthen and shape Tinbergen's quantitative model-driven direction.[4][5]

Based on those certainties—gradually adapted over time through a range of mainstream models—the economic discipline interpreted and partially regulated the industrial and financial dynamics of the twenty century. However, as social, economic and environmental relations have undergone profound transformation, the limitations of these frameworks and the lack of theoretical tools to interpret the emerging reality are becoming increasingly evident. The natural sciences are now forcefully entering the domain of the social sciences to address the irreversible warming of the atmosphere mainly caused by carbon dioxide emissions from both historical industrialisation and ongoing development in emerging economies.

As an economist, I firmly believe that history and the natural sciences are essential to understanding economic life on the planet. The limits and scope of this contribution, though, need to be made clear. I do not intend to venture into areas of research that are not my own. However, following Simon (1962, p .467), I shall make reference to areas of knowledge where I am "not expert—perhaps not even literate—", as the principles and vision introduced by quantum physics.

First of all, the threat of natural disasters means that we must deal with a new form of uncertainty; uncertain expectations on frequent natural catastrophes overlap with the known relationships between governments, institutions and populations. Uncertainty of these processes does not concern the risk of incomplete knowledge that undermines the results of the scientist. It is intrinsic to the processes themselves.

Uncertainty, as we know, is different from risk;[6] nor does uncertainty only address the risk of incomplete knowledge. In technical terms, this uncertainty does not relate to the epistemological sphere of the discipline, but to the 'ontological' sphere, to the reality of the expected processes. It thus offers the special opportunity to reconsider an interdisciplinary approach for the economic discipline.

The economist's intuition, which is pragmatic by nature, led me to seek answers in the revolutionary approach of the quantum theory and refer to the concept of uncertainty introduced by that theory in a quite different context, i.e. the analysis of microphysics. Insights from the quantum theory offer a particularly valuable perspective, showing how new ideas shape different visions of the world.[7] Indeed, chance and probability play a crucial theoretical role also within this new uncertainty which in my opinion should be transferred into the economic discipline to interpret the collapses we are experiencing in our time. 'Yes, chance has a crucial role and "God plays dice", we may answer with Heisenberg to Einstein's objection.[8]

[4] The discussion between Keynes and Tinbergen on this issue (1931–1934) is enlightening. For Keynes uncertainty is unknowable, subjective, not approximable with statistical probabilistic models; on the contrary, Tinbergen has a quantitative approach to uncertain events; he considers uncertainty as a risk, to be described in quantitative probabilistic, statistical models. Thus, Tinbergen opens the way to econometric models. Current economic developments have been critically defined "play-metrics". See also Galavotti (2005).

[5] As Majorana underlined: "It is important that the recent principles of Quantum Mechanics have led to the recognition of the statistical nature of the ultimate laws of elementary processes (in addition to a certain lack of objectivity in the description of phenomena). This conclusion has made the analogy between physics and the social sciences substantial, revealing an identity of value and method between them'. in Majorana and Esposito (2006, p. 261). Majorana then goes on to show the turning point between the deterministic method of classical physics and the development of quantum mechanics. Criticism to economic determinism has been growing in economics, in the late twenty century. See, among others, Sylos Labini (1967), Lunghini (1967), Pasinetti (2007) and Scazzieri (2015).

[6] Keynes was very clear in explaining the concept of uncertainty after the publication of The General Theory (Keynes, 1936) "By 'uncertain' knowledge, let me explain, I do not mean merely to distinguish what is known for certain from what is only probable. The game of roulette is not subject, in this sense, to uncertainty. The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence. About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know." *(*Keynes 1937). As Gammaitoni and Vulpiani write (2019) 'It is well known that, according to the classical mechanics, the motion of a fundamental body is entirely determined by the initial conditions (position and velocity) in which the body finds itself and by the forces acting on it. According to this view, which gave rise to the mechanistic conception of nature (…); the entire future is implicit in the present, in the sense that it can be predicted with absolute certainty, provided that the present state of the universe is fully known' in a purely deterministic conception of nature. With quantum physics, 'physics has been forced to abandon its traditional approach rejecting, in all likelihood definitively, the absolute determinism of classical physics'. (ibidem, p. 137–138 and Ch.10).

[7] Again Gammaitoni and Vulpiani (2019, pp. 137–138): 'In a strictly deterministic theory, there is no room for random events. Chance is interpreted here as being due exclusively to our ignorance of the details of the causes that produced that event. Newtonian mechanics is undoubtedly a deterministic theory, while quantum mechanics is not.'.

[8] F.S.C. Northrop's (1958, p. 13–14) offers an interesting explanation: 'to understand Heisenberg's response to Einstein's criticism, one must bear in mind the difference that the concept of probability has (a) in Newton's mechanics and Einstein's theory of relativity and (b) in quantum mechanics where the concept of probability or chance enters into the definition of the state of a physical system and in this sense into the object of research of quantum mechanics, whereas this is not the case in Newtonian mechanics or Einsteinian theory of relativity'. Cf. Keynes (1931, 1936, 1937). See also Heinseberg (1958) and Majorana (1942, p.66). Majorana goes on to show the turning point between the deterministic method of classical physics and the development of quantum mechanics. 'Determinism,' Majorana con-

On the other hand, the **irreversibility** of economic relations finds formal expression in the concept of entropy, so effectively taken up by Georgescu-Roegen (1971) from the second law of thermodynamics.

Finally, to be clear, the vision of this paper is far from the application of quantum mathematics to financial models (the so-called Black and Scholes models, named after the founders of this line of models (1973), with Merton (1973).[9] I intend to apply the concepts of chance and probability to an open system, far removed from those analyses. The aim of the research is to help discovering how the economic discipline can theoretically address the new uncertainty brought about in the economy in particular by the energy/climatic imbalance that has burst into our lives, relying both on a set of mathematical tools taken from classical statistical mechanics (Boltzman, Maxwell) and from quantum statistical mechanics (Bohr, Born, Dirac, Schrödinger, Heisenberg, Pauli), in an open system.

Finally, the second pillar of my research is the demise of the centrality of market relations. The economic impact of natural catastrophes and the economic policies to deal with them cannot be traced back to market laws. They require an economic *cooperative approach* to replace confrontation through the market. The *complementarity between microparticle* (the individual) *and macroflows* is also essential. It is not solved by the principles of optimization of the von Neumann–Morgenstein game theory (1944) because we reject here the centrality of the market.

The overall aim of this research that has been ongoing for a number of years is to shed some light on the way in which uncertainty on economic future events can be framed and analyzed. I would like to propose the re-examination of the economic discipline within an interdisciplinary framework, based on a cohesive set of concepts and tools especially linked to the vision introduced by quantum theory, that, I believe, are appropriate to interpret the dynamics of economic challenges of the new millennium. On the other hand, the principles of thermodynamics help to define irreversible phenomena, and the theory of relativity is also crucial to follow the dynamics of interdependent events. This is the aim of my research, some key points of which are summarized in this article.

I rely on the curiosity and goodwill of the reader to deepen some of the insights I present here.

2 Uncertainty

2.1 Uncertainty of processes

There is little doubt that economists today are uneasy when confronted with the complexity of change and with the challenge of making predictions on the dynamic impact of economic policy. This is evident in the limited but significant overlapping efforts in different research fields of the economic theory. Contrasting climate change is a major example; yet, several other examples mark the field. Among others, Nobel laureates Kahneman and Tversky (2000) have made pioneering contributions to understanding complex individual behaviour, while scholars such as Sabel and Victor (2022) and [10] Keohane and Victor (2011) and the Nobel laureates Banerjee and Duflo (2022) and Ostrom (1990) have provided valuable insights into the collective decision-making processes required to address international economic developments and climate change. The necessary theoretical renewal involves rethinking microeconomic phenomena,

Footnote 8 (continued)

tinues, 'contains a real cause of weakness: the immediate and irremediable contradiction with the most certain data of our consciousness'. The characteristics aspects of quantum mechanics as it differs from classical mechanics are (a) that there are no laws in nature that express a fatal succession of phenomena; (b) a certain lack of objectivity in the description of phenomena'.

[9] The Black and Scholes model (1973), is the first and today the most widespread of these models for hedging the risk of financial portfolios with derivative assets, the options. It won its authors the Nobel Prize. However, the extraordinary loss suffered by the financial fund created by the authors themselves, the year after the 1997 Nobel Prize, is little known but significant. More catastrophic has been the spread of these algorithms set to act automatically in response to specific market trends, thus creating generalised sell orders when assets exceed value thresholds considered at risk in the algorithms: this practice amplifies the magnitude of losses. The spread of these practices has contributed to the instability of highly integrated global financial markets. I recall for all the 1987 crisis, when the automatic and simultaneous order to sell, above a certain price threshold, caused the financial markets to collapse, creating an obvious international contagion. Even worse was crisis of 2008, based on a non-pragmatic reading of the assets in which unsafe mortgages were packaged and the algorithm aimed at defining the dynamics of derivatives has made the final stretch on the path to financial catastrophe. In a nutshell, I would like to stress that the value of assets is purely uncertain, subject to a cloud of possible future events and that financial instability is enhanced by the spread of homogeneous models to price derivatives. Today, the situation has slightly changed. The use of financial models based on quantum relations would allow the superposition principle to include innumerable possibilities of evolution of the interacting variables in the period under consideration. The quantum computer is the tool that will allow this enormous amount of information to be exploited within a reasonable timeframe. However, awareness of the conceptual difference between 'risk' and 'uncertainty' remains central. In other words, I note that although the theoretical models of finance have reached some insights from quantum theory, their use has not gone as far as the change implicit in that vision, which is still completely alien to the discipline of economics.

[10] Sabel and Victor (2022) propose the theoretical framework and a few examples of experimentalist governance as a collective answer to the uncertainty of events.See also Boncinelli, Ereditato (2022)

particularly the participation of individual behaviour in the waves of macroeconomic dynamics.

The theoretical challenge is clear. As both spectators and participants in the unfolding drama of life, we have long relied on the principle of causality to order our perceptions. However, today this principle appears insufficient for capturing the complexity and virtually limitless possibilities for the future that make an open model essential. Traditional quantitative forecasts of economic models must give way ex ante to different potential paths. Abandoning strict economic determinism and certainties is essential to address transitional processes.[11] The energy and digital revolutions, alongside advancements in artificial intelligence, are at the forefront, pushing us to view the world as an open system, characterized by historical and economic leaps.[12]

The intuition of the potential multiplicity of future states is interpreted by *waves of potential event*s, as in the foundations of quantum theory. However, the intermediate processes, i.e. the transition between different states of unstable equilibrium, disappear from view; they give rise to a new, different state, according to a *principle of transformation*.

An example may intuitively illustrate the theoretical concept. I would define it "A *walk between two lampposts*." It is evening. Through the window, I observe an individual walking briskly along the opposite pavement, illuminated briefly by a lamppost. Our walker is visible, wearing a winter coat against the cold. Then, the individual's image fades into darkness, becoming indistinct until the next lamppost lights him up again, now in a new state. In the darkness between lampposts, however, the transformation from one state to the next unfolds, unseen, yet essential. I cannot perceive or know the real dynamics of his journey. I neither see nor understand what transpires. The passerby may have stopped to tie a shoelace, slowed to check a text message and respond, been delayed by something external, like a dog, or he may have continued at a brisk pace, or even changed route due to a sudden call. Each scenario leads to a different outcome. The second lamppost will reveal a new, temporary state of the passerby. The duration, speed, and even the direction of the process, cannot be determined in advance.

This is not merely a matter of perception or hidden variables, i.e. the epistemological consideration of the phenomenon; the potential reality is variable, multifaced and diverse. The time of transition is merely a scalar outcome that can only be statistically measured ex post. The end point of the walk, the new state, is not a function of time, it is a function of the subject's interaction with various variables, whose probabilities we can hypothesise influencing the path; it is a quantity to be modelled statistically and confronted with experiments. By selecting among an array of possible variables and relationships—such as a message that slows the motion of the passerby, the evening cold that leads him to a quicker pace or a thought that prompts a change in direction—we can give different probabilities to those events, assign them different strength on the basis of historical phenomena statistically reconsidered, and define their relative influence towards the process of transition; the intermediate states need to be estimated probabilistically.

Likewise, the possible motion paths remain undetermined. I lack specifics on the transition process, including both actual and possible occurrences during this period of change. Most important, given this uncertainty and the consequent absence of knowledge, in technical terms I cannot assume the invariance of translational axes over time. Intermediate processes vanish from perception between one provisional equilibrium state and the next, embodying fundamental uncertainty.

Chance is pivotal in determining the real process and to interpret the process towards a new state, which may not even manifest if the passerby changes direction. Physicist G. Chaitin, from the Quantum Centre in Singapore, along with Eckert, defines chance as "statistical incompressibility"; they present a theorem which shows that the existence or non-existence of chance cannot be proven.

This approach requires the formulation of an array of multiple hypotheses. The scholar's role is to identify the most the probability and magnitude of potential phenomena and reactions on the basis historical statistics. The strongest reaction (feedback) that has the highest probability to occur

[11] The theoretical elaboration of this view would require a separate essay. Here it is useful to refer to Northrop (1958), who gives a precise definition of the different forms of causality, as a relation between objects, as a relation between different states of the same object or as the same system of objects at different times. This leads to an analysis of the relationship between causality in the strict sense, which he defines as mechanical causation and the deterministic relationship (pp. 21–23). From the unification of potentiality and mechanical causation in the strict sense derives, for Northrop, the original principle of the methodology of quantum theory. (p. 31); i.e.: 'whereas causality in Newton's and Einstein's physics is understood in the widest sense and is therefore both mechanical and deterministic, in quantum mechanics it is understood in the narrowest sense and is, therefore, mechanical but not deterministic', p. 23. Northrop is illuminating in emphasising 'the consistent unification of potentiality and mechanical causation in the narrow sense' (p. 31). See Hicks (1979); let me also refer to Termini (1981,1984). For further discussion see Taleb (2008).

[12] "In devising relativity Einstein reinvented space and time", the redefinition of causal relations defined in time follows. Cf. Lindley (2008, p. 130). Quantum theory has complemented the established paradigm of classical physics in the first decades of the twentieth century, for the analysis of microstructures, fundamentally breaking the existent vision of the world, with far-reaching methodological implications for the fields of chemistry, biology and astronomy, to name a few. Yet, the foundational tenets of classical and neoclassical economics were not affected by it.

gives the result that will prevail at the end of the transition from one state to the next.[13]

Thus, the principle of uncertainty—which forces us to disaggregate intermediate opposite phenomena and analyse the relative probability of their occurrence—helps us to organise our thinking, especially when we analyse the transitional processes separating one temporary equilibrium from another in social relations. The dynamic processes disappear when we compare two states of equilibrium; however, they require formal representation; we may take the tools from the quantum paradigm. Heisenberg's matrices and Schrödinger's functional waves can help.[14]

Furthermore, in the dynamics of constantly moving processes, the interaction between subjects produces new realities and a new context, according to the *principle of interference*.[15] Consequently, the new vision must permeate the theoretical framework of economics as a discipline.

In the concepts of *superposition*, *interference* and *entanglement*, I found the analytical tools that could unlock the rigidity of the classical economic method. Future potentialities comprise different outcomes—indeterminate ex ante, yet real and measurable ex post. A simplified analogy that pragmatically illustrate the range of possibilities is contained within a block of marble: after a dynamic process, it could become a staircase step, a tombstone or, with Michelangelo's creativity, a statue of Moses—one of many latent possibilities brought to life.

Once again, the new path has been traced by physics. The emergence of quantum physics has, in the first decades of the twentieth century, transformed our understanding of the world in the above-mentioned direction. Quantum theory has complemented the established paradigm of classical physics, for the analysis of microstructures, fundamentally breaking the existent vision of the world, with far-reaching methodological implications for the fields of chemistry, biology and astronomy, to name a few. Yet, the foundational tenets of economics, classical and neo-classical, were not affected by it. Despite the seismic shifts in scientific understanding, economics has remained largely tethered to the foundations of classical and neo-classical market theory. It has become imperative for economists to view the role of humanity as part of a complex universe.[16] Humanity is part of nature, as Spinoza understood and articulated, among others, preceded by Lucretius and followed by thinkers like Goethe and Einstein. Durkheim' (1893, trad 2016) analysis of organic social systems burst into the picture.

Several attempts to describe the economic policy of climate change and financial trends in terms of probabilistic risks have not been successful, though, as they do not take into account the difference between risk and substantial uncertainty. We can refer to Weitzman (2009), among others, who gives us a plain illustration of this issue; he shows that the economic consequences of fat-tailed structural uncertainty (along with uncertainty about high-temperature damages) can readily outweigh the effects of discounting climate-change policy analysis."

2.2 The fallacy of economic determinism: chance and waves of potential positions

Uncertainty precludes the possibility of analytical determinism in the field of economics. From a methodological perspective, the potential for unforeseen events and different realities makes the future outcome of an economic process inherently unpredictable. This contrasts with assuming a necessary, measurable link between cause and effect; the principle of causality often fails to yield effective results. This is evident in econometric models, where the common practice of adding an "error" to account for the gap between forecasts and reality is widespread in quantitative macroeconomic models.[17]

In the economics of climate change, this problem is crystal clear. In a perfectly understood non-stochastic world standard, duality theory says that price and quantity tools are essentially mirror images and can be used interchangeably. However, where risk and uncertainty are important and knowledge is highly imperfect, we have to consider the

[13] A recent example of uncertain outcome is the uncertain imposition of tariffs on international trade, which reduce trade flows and may dampen global economic growth.

[14] The quanta paradigm introduced discontinuity and unpredictability into physics that had to be mathematically dealt with, via the probability wave functions elaborated by Schrödinger or Heisenberg-Born matrix algebra (the matrix mechanics) (Schrödinger 1926; Heisenberg 1958).

[15] Born (1926) "It is no longer possible to say what the specific outcome of a collision—interaction-would be. You could only specify the possibilities of range of outcomes". "There the whole problem of determinism arises", Born wrote. "I myself am inclined to give up determinism in the atomic world". See also Dirac (1930, 201), Schrödinger (1931) and Feynman (1985).

[16] The extensive work of the early twentieth-century physicists (Bohr, Born, Sommerfield, Schrödinger, Heisenberg, Pauli, among others) provide invaluable insights for economists aiming to understand global economic activity.

[17] A recent example of uncertain economic outcome, indirectly related to climate change is offered by the Russian invasion of Ukraine that had the potential to set in motion contrasting economic drives toward decarbonisation. Indeed, two opposite impacts might have followed the gas crisis. Rising gas and energy prices could slow the energy transition by increasing costs. Yet, they could also have the opposite impact, accelerating the energy transition by pushing governments and companies to increase their use of renewables, thus promoting energy savings and driving technological innovation toward non-fossil sources. These opposing paths should be included ex ante in the wave of war potential outcomes. See Marzetti Dall'Aste Brandolini and Scazzieri (2011) and Termini (2024).

relative merits of each. For the most part, as Stern (2008) has warned, in climate economics “we ignore the difference between risk and uncertainty (where the latter is used strictly in the Knightian sense of unknown probabilities), but it is a very important issue and a key topic for further research.” I will come back to this issue in par. 3.2, when considering when considering the different streams of climate models.[18]

Indeed, many examples, can be drawn from the economic discipline showing how methodological determinism produced flawed economic results. An example may be taken from the failure of a macroeconomic model of fiscal policy—the Laffer’s model—to provide the expected results, while in microeconomic analysis, the practice of "optimising" financial portfolios for individual traders has contributed to recurring crises in global finance[19] These examples illustrate how theoretical predictions are frequently contradicted ex post by statistical data. Yet, these models persist at the core of the dominant economic paradigm.[20]

The first example is offered by the Laffer’s model that assumes a causal link between lower marginal tax rates, profits and income growth. In essence, Laffer stated that a decrease of the marginal tax rate, implying a reduction of the tax burden on private revenues will make aggregate income grow, by increasing internal demand and private investment. As a result, the total value of tax revenue with a lower marginal tax rate should remain unchanged and provide a stimulus to national economic growth. This theory, however, has been disproved by statistical results, as other factors invalidated the process when applied by Reagan (US Congress, 1981) and then by Trump (US Congress, 2017). The financial and speculative outflow of those unexpected earnings produced opposite effects to those implied by the model. Indeed, in the globalised financial world, these outflows contributed to the fragility of the international economic framework and they did not add to the growth of national income or to aggregate tax revenues.[21] In macroeconomic policy, Laffer's model (2004) shows that the application of a causal principle does not account for the different potential future outcomes inherent in economic processes. This reveals the complexity of processes and the role of uncertainty and chance.

On the opposite direction, it is enlightening to counterpose the results of Roosevelt's response to the 1929 crisis that was far more pragmatic and contextual than the deterministic approach assumed applying the equations of the “Laffer’s model”. In the wake of a political drive, Roosevelt maintained high marginal tax rates while funding major infrastructure projects and social protection measures, which helped to pull the US economy out of the depths of the crisis.[22] Notably, Roosevelt’s economic policy proved effective through its clear vision for American society, supported by a detailed analysis of the nation's potential and present conditions.

A theoretical turning point followed. The outcome of Roosevelt’s economic policy influenced Keynes’s theoretical revolution and contributed to foster Keynes' innovative perspective from the rigidly framed version of his Theory of Money (1930) to the opposite, flexible and probabilistic approach of The General Theory (Keynes, 1936). Accordingly, in the General Theory Keynes opened a methodological path, introducing a new framework of uncertainty—the expectations of the “animal spirits” and the “conventional” level of the rate of interest—in the economic theory.[23]

Keynes' approach was the result of introducing uncertainty as a dominant factor in a monetary economy, focusing his analysis on interest rates, investment and employment. In his new view, the interest rate is a conventional variable whose value is subject to the unpredictability of financial speculation rather than to the market equilibrium

[18] From Walras and Pareto, economists transferred the regularities described by classical mechanics, following Newton's laws, to macroeconomics and even to finance, for example, naturally without achieving adequate predictive capacity and sometimes accumulating colossal losses. Majorana recognised the value of statistical laws in the social sciences as opposed to the mechanistic approach of classical mechanics transposed into the social sciences, in order to analyse the stochastic nature of social events. Only later did the theory of statistical probability proposed by Boltzman and analysis based on stochastic processes entered the field of econophysics, as defined by D. Cocolicchio, L. Grilli, L. Maddalena (2006). This led to the representation of the price trend of financial derivatives (options) in the Scholes and Merton model (1973).

[19] The development of these portfolio models ultimately relies on a simplified form of quantum theory, but without capturing its overall vision.

[20] The co-founder of Oaktree Capital Management analyses the difficulty of correctly predicting the future in the financial markets, 19 July 2024. "As I pointed out in my ‘The Illusion of Knowledge’ (September 2022), a macro forecasting expert can in no way produce an estimate that correctly incorporates all the many variables capable of affecting the future, as well as random influences about which little or nothing is known." Howard Marks—known for predicting the dot.com bubble boom and bust—analyses the risks of overconfidence in one's beliefs and the fallacious nature of forecasts.

[21] It is interesting to note that for most of the twentieth century, US marginal tax rates remained high, averaging around 70% and peaking at 90%. Kennedy reduced them in the early 1960s, at a time when the economy was flourishing. The failure of the Laffer’s approach to increase national economic growth is linked to the integration of financial markets and to the profit maximizing behaviours of high-income citizens: in Italy, e.g., in 2023 only 16% of profits remained in the country and 84% flew to foreign financial markets.

[22] The Economic Recovery Tax Act (1981), signed by Reagan, reduced the highest marginal tax rate for all types of income from 70 to 50% and then to 28%. D. Trump’s Tax Cut and Job’s Act lowered individual income tax rates, including the top marginal rate from 39,6% to 37%.

[23] See also Keynes Treatise on Probability (1921).

of savings and investment, as was the case in neo-classical economic theory. Moreover, investment, that is key to economic growth, depends on entrepreneurial uncertain expectations on future profits (the "animal spirits"). This is the new perspective that formed the theoretical ground of The General Theory of Employment, Interest and Money. It is interesting to notice that Keynes' own economic revolution was influenced by the "spirit of time", as following Knight he differentiated risk and uncertainty, also in finance.[24]

These influences, in conjunction with other factors, prompted Keynes to make the theoretical leap towards the imprecise flexibility that was necessary to interpret the transition during the crisis of the 1930s. Keynes's own experience in commodities speculation, the end of the certainty of currency values that had been the hallmark of the gold standard and, finally, the pragmatic approach of economic policy required to build the Bretton Woods Agreements after the Second World War, all provided Keynes with the experience that helped him to envisage his theoretical vision of multiple potential economic outcomes, as well as the essential categories for understanding the emergence of a globalised financial landscape.

Unfortunately, Keynes's innovative approach was basically overlooked. In the General Theory, Keynes proposed that uncertainty should be regarded as a distinct logical category, separate from risk, influenced by Knight's concept of uncertainty marked by chance.[25] However, this methodological intuition did not gain sufficient ground to influence the direction of economic theory. Instead, the methodology of The General Theory was quickly "normalised" Hicks (1939) into a rigid framework, which dominated economic theory at the time and continues to exert considerable influence today. The only enduring aspect of Keynes's vision was its central tenet, which questioned the capacity of the market to regulate itself and underscored the necessity for countercyclical public sector interventions. Yet, the transformation of his reasoning in the deterministic IS/LM curves took the soul out of Keynes' theoretical creation. And this approach has prevailed in various forms up to the present day.

The second example is provided by the stream of models that predicts the optimising behaviour of traders in managing financial portfolios, focusing on profit maximisation and risk hedging. They all follow the model introduced by Black and Scholes (1973), using a shared algorithm. I refer to Taleb (2008) for an extensive, illustrative discussion on the disruptive outcomes, which may be, and have been, produced by the application of these financial models.

Both theories are normative and have caused substantial harm. The widespread adoption of the financial model has undoubtedly contributed to the standardisation of market participants' behaviours, which, in turn, has caused repeated disruptive financial crises in the highly interconnected global markets. The issue is once again methodological: we need to shift away from economic determinism in view of fundamental uncertainty of the transmission mechanisms.

Today, the spirit of time is again opened to deal with an uncertain world, in transition. Several different theoretical directions mark the field. A strong one follows the evolutionary path of natural sciences. The evolutionary economics literature argues for the need to follow the interactions between technological and institutional changes that foster structural dynamics in economic systems; "novelties and changes in one system dimension, often resulting from the adaptation and learning behaviours of individuals give rise to pressures for changes in other system dimensions, leading to an evolutionary process of transfromation of economies". Other approaches have focused on the relationship between non-reproducible scarce resources and industrial innovations[26]; finally, others include social feedbacks into the analytical frame of the experimentalist theory.[27]

The time is now ripe to revisit that vision, possibly providing some essential concepts which address uncertainty and the overlapping paths of future economic outcomes through potential waves formed by microparticles, the individuals.

2.3 Macrowaves and microparticles

The definition of the corpuscular particle—the individual—provides an explanation for the specific behaviour observed within its orbit. Social fragmentation, which today cannot be represented politically in traditional categories, concerns the individual. There is no reason why a leap cannot occur between different economic orbits.

The principle of complementarity recognises the necessary complementarity, between the microparticle (the individual in economics) and the macrowave (the dynamics of the economic and social spheres). Yet, different individuals in economics are elements whose behaviours contribute to

[24] Cf. the debate on the "finance motive" that opposed Keynes and Roberton (1937).

[25] Cf. Knight (1921) and Keynes, A treatise on Probability (1921).

[26] The problems of resource management and pollution control related to issues in development planning are addressed by Dasgupta (1982). The economic push towards resource-saving technological innovation, driven by resource scarcity, is considered by A. Quadrio Curzio (1986) and Monasterolo et al. (2019). See also Carraro et al. (2003) Endogenous technical change in environmental macroeconomics, Resource and Energy Economics, 25, pp. 1–10, Weitzman (2009) and Wagner and Weitman (2015).

[27] An application of the experimentalis theory is in Sabel and Victor (2022).

shape the trajectory of the macrowaves. Individual participation—e.g. in contrasting global warming—significantly influences the macroeconomic dynamics of a socially fragmented world. This representation is far away from the concept of the "representative agent" in optimisation models.

In the process of aggregation, the microgranularity is lost, and the individuals apparently disappear. However, the particle continues to exist according to the principle of complementarity between particles and waves. An example intuitively illustrates this concept. Like water droplets in the sea, microparticles merge into the wave which then breaks on the beach; while they seem to disappear, their individual existence endures, shaping a wave. This micro–macro complementarity is also a fundamental concept in economic theory.[28] It is essential to define the climate policies.

Finally, everything is connected in space and time; entanglement rejects the principle of separability between sciences and the separation of elements from their environment. This led to the development of systemic theory in the 1960s, opened by Simon (1962), which shows that a system is more than the sum of its parts.[29]

It is then essential to consider the analysis of an ecosystem that requires interdisciplinary knowledge—including geography, volcanology, meteorology and seismology—in the economic study of the climate.

Moreover, the concept of space–time in economics has always been that of a world of separation. But if there is a state of inseparable connection between particles, this cannot be described by the concepts of space–time as an absolute, separating reality; the distinction between subject and object of knowledge is impossible. This notion underpins the movement of flocks that are not a function of time.

An attempt to deal with complexity has been to consider the behaviour of adapting systems, following Simon (1962), using the concepts of feedback, homeostasis (e.g. in ecosystems) and evolution, to analyse adaptiveness in terms of selective information.[30] They enable to build a system of reference for considering a wide range of situations. Complex systems have been considered, where complexity takes the form of "hierarchy", the complex system being composed of subsystems that in turn have their own subsystems. (i.e. they are decomposable, each following a "boss"); then the time required to emerge through evolutionary processes is inquired.[31] Simon for example relies on a matrix system to analyse the behaviour of near decomposable social systems.[32]

This is one key that enables economics, among the social sciences, to transcend the constraints of determinism, fostering a more nuanced understanding of the relationships underlying the transitions. As Edgar Morin (2017, p.45) notes in his study of complexity, the search for simplicity often leads to the discovery of complexity.[33]

This *superposition principle* permits multiple event alternatives to be superimposed (economists describe this as an "ex ante" condition), driven also by the role of chance, which allows for the simultaneous potential of multiple outcomes. The likelihood of a given outcome includes different results until one outcome alone materialises ex post. This concept has been examined in further detail. The contribution by H. Simon has given a theoretical frame to analyse complex systems. It entails the role of interference and probability which is the focus of a vast literature.

Interference[34] however, differs fundamentally from classical probability. In classical probability, variables are assumed to be independent, such as the faces of a die, making probability additive. The superposition principle, though, requires that probability amplitudes be combined, resulting in a cross term. The probability amplitude is calculated using to express the phase relationships of the waves

[28] See Caravaggio e Sodini: "regardless of the time setting, the dynamic systems governing the evolution of both economic and environmental variables are able to exhibit the occurrence of cyclical dynamics, multi-stability or indeterminacy". "These heterogeneities may concern (i) the introduction of environmental variables affecting the system both as a production input and a consumption good, or (ii) the inclusion of a multiplicity of environmental resources both in the utility and production functions. The effects of this kind of heterogeneities on the dynamic properties in models focusing on the coevolution of economic and environmental variables still represent open questions on which a scholar's agenda may concentrate upon." See also Pauli and Villars (1949).

[29] The development of systemic theory also introduced the concept of bounded rationality, challenging the neoclassical concept of rational individuals. See also E.Morin (2017)

[30] See Simon (1962, p. 467), Shannon and Weaver (1949).

[31] H. Simon explains:"The main theoretical findings from the approach are in two propositions: "a) the short run behavior of each of the component subsystems is approximately independent of the short run behavior of the other components; b) in the long run, the behavior of any one of the components depends in only an aggregate way on the behavior of the other components" (1962, p. 474). Unfortunately, Simon considers the main variables of economic dynamics the price and quantities of commodities, as in a market dominated system. This is not the case for the analysis of climate, that theoretically requires open systems to be analyzed. See also at the Santa Fe Institute: W. Brian Arthur*;* John H. Holland*;* Doyne Farmer, who worked on financial markets as complex systems and systemic risk. Finally, Samuel Bowles integrated behavioural insights and institutional complexity into economics.

[32] Von Neuman and Morgenstern (1944) introduced the game theory to analyse the agents' strategic behaviour aiming at maximizing profits under constraints; they use matrices in a dynamic framework that follows the quantum tools, to determine the payoffs of economic agents. Probability enters thus into the picture to describe agents' utility maximizing behaviours in the market. However, the centrality of market relations is at the heart of their analysis.

[33] See also the physicist Chaitin (1975).

[34] See Schrödinger (1935).

and to interpret interference phenomena, *i.e.* whether the waves are in phase or out of phase; the probability is an integer whose sum is 1.

Finally, as already mentioned, the principle of interaction provides an additional insight: interference should be viewed as a creative process. The conjunction of two particles (events) creates a new reality.[35]

Just as quantum physics revolutionised classical physics, it has also provided the tools to formalise these new perspectives in economics. In the realm of process uncertainty, the *probability wave*—represents a tendency towards specific outcome. It provides a quantitative interpretation of the concept of power, describing, within a multidimensional space, overlapping potentials and the almost limitless possibilities inherent in events, given chance and the uncertainty of their actual occurrence. This potential persists until the wave function "collapses," allowing one outcome to become real and enabling ex-post verification. Similarly, the matrix system addresses multifaced dynamic processes.

3 Climate

3.1 Overlapping paths: the climate crisis

A crucial area where economic theory must find the impetus to move from deterministic models to the perspective offered by open systems concepts—interdependence, entanglement, interference of the processes—is climate change.

Climate is a domain in which pathways and processes are to be framed by overlapping possibilities, including the spur to technological innovations that follows the urgent need to decarbonise the planet. There is no certainty as to which force will dominate. I will briefly consider this point in the following.

The Intergovernmental Panel on Climate Change (IPCC) provides a thorough analysis of the impact of radiative forcing on global warming, illustrating both positive effects (e.g. Co_2 emissions warming the atmosphere) and negative effects (e.g. aerosols and albedo cooling it). Figure 4 shows the composition of these positive and negative phenomena, with the probability distribution of anthropogenic forcings highlighted in the red area.

The principles that govern the movement of energy and the laws that explain them are based on elegant, simple and comprehensive criteria. They also have an impact on the micro- and macroeconomic spheres. However, to interpret and counteract climate change, it is essential to consider the properties of interference and entanglement.[36] The mathematical language to express these processes within Hilbert vector space, defines a complete space that incorporates the principles of superposition and interference. The amplitudes associated with ground states are numbers that combine into set of concepts and a possible mathematical formulation to constructive (positive) and destructive (negative) interference, representing, for example, the sum of positive and negative radiative forcing on global warming (Fig. 5).[37]

The following Figs. 6, 7, and 8 illustrate the multiplicity of the economic impact of climate phenomena and the largely unpredictable nature of their occurrences.

The graphs (6, 7) show anomalies in global land surface and ocean temperatures (1880–2023) in °C.

As defined by the IMF, the INFORM Risk Index is a global, open-source risk assessment tool for crises and disasters. The CLIMATE-RELATED INFORM Risk Index is an adaptation designed to centralise and distil climate-related risks. It encompasses three dimensions: climate-related hazard and exposure, vulnerability and lack of coping capacity. The climate-related hazard and exposure dimension captures the likelihood of physical exposure to specific climate hazards. Vulnerability reflects the economic, political and social characteristics of communities that may face destabilisation during a hazard event. Lack of coping capacity measures a country's ability to respond to disasters, considering formal, organised government-led actions and the infrastructure that supports disaster risk reduction. The maps illustrate the composite climate-related INFORM RISK indicator and its Hazard and Exposure component. Risk and exposure data for 2022 have been sourced from the IMF website (Fig. 9).

3.2 Climate theory and uncertainty

A vast economic literature addresses the issue of contrasting climate change having assessed the anthropogenic contribution to the warming of the planet, in particular through the emissions of carbon dioxide (CO2). (IPCC Reports).[38]

[35] We find these principles organized as a coherent set of concepts in the quantum paradigm. See Feynman (1985), Dirac (2019, 1930). Cf. also Simon (1962).

[36] Here the language borrowed from quantum mechanics is employed as suggestive of a coherent interpret and predict these expected economic processes.

[37] [39] The quantum computer is the current totem intensely investigated technologically and experimentally enabling immense calculations at an acceptable speed such that a vast array of probabilistic pathways can be processed in minimal time. It may be the game changer that will enable the analysis of the huge number of data needed to elaborate the paths of possible processes related to the economic impact of climate change.

[38] See the Intergovernmental Panel on Climate Change (IPCC) Reports. In IPCC AR6 2021–2023, the Working Group I analyses the physical science basis of climate change. After the First IPCC Report (1990) it is now evident human activities are responsible of the global average temperature increase. From 1850 to 1900 that increase of warming is about 1.07 °C, of which carbon dioxide (CO_2) alone con-

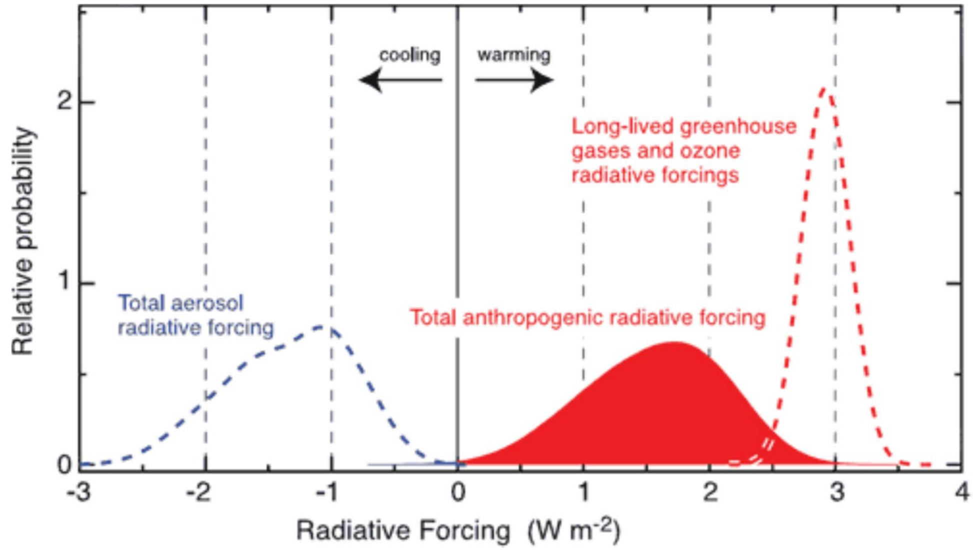

Fig. 4 Probability distribution function for the combined effect of anthropogenic radiative forcings. The three cases presented are as follows: the sum of all anthropogenic radiative forcings (within the red area), long-lived greenhouse gases and radiative forcing due to ozone (red dashed area), and negative radiative forcing due to aerosols, albedo and clouds (blue dashed area). Notably, these three probability density functions exclude natural radiative forcings, such as solar and volcanic effects. *Source*: Forster et al. (2007): Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (IPCC AR4 Fig. 2.20b)

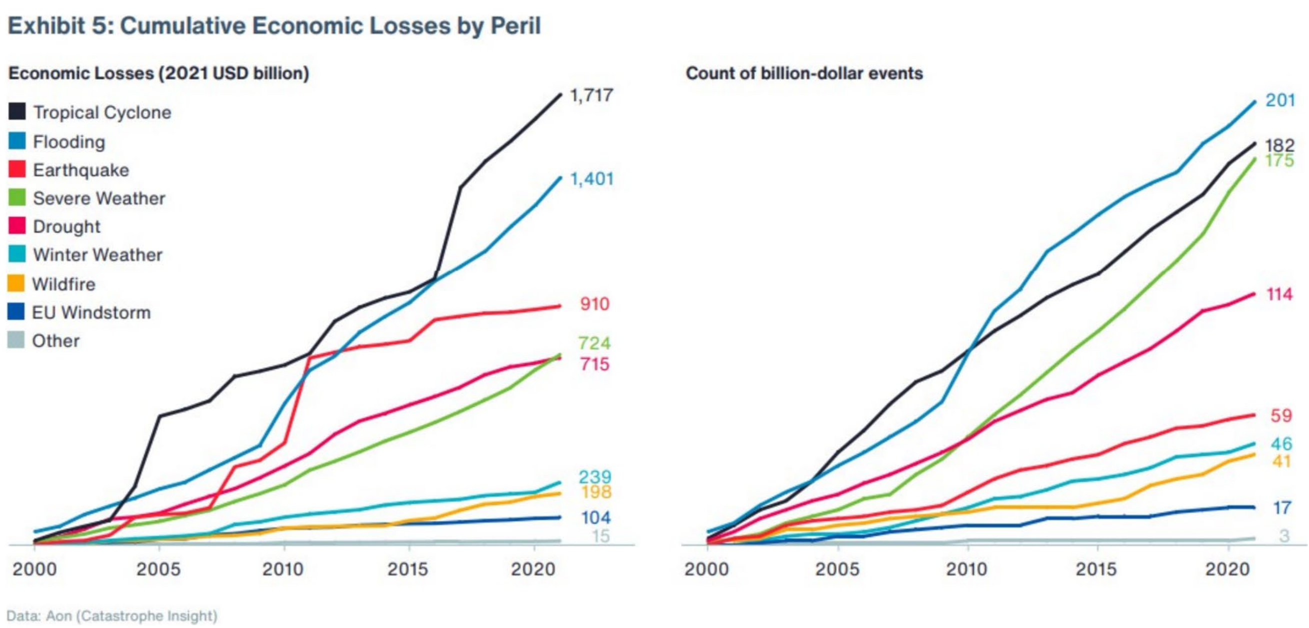

Fig. 5 *Source*: Aon: https://www.aon.com/getmedia/1b516e4d-c5fa-4086-9393-5e6afb0eeded/20220125-2021-weather-climate-catastrophe-insig.pdf

Footnote 38 (continued)

tributes about 0.8–0.9 °C. Other greenhouse gases (CH_4, N_2O, etc.) add a part, while anthropogenic aerosols (such as sulphates) have a cooling effect. "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Carbon dioxide is the main driver of this warming (66%)."— IPCC, AR6 WGI SPM, 2021.

The theoretical literature converged to solve two main issues: 1. to evaluate and quantify the economic consequences of the warming of the planet; 2. to elaborate the policies to contrast climate change, quantifying the costs of decarbonisation and comparing them with the avoided costs of the consequences of climate change. A very large

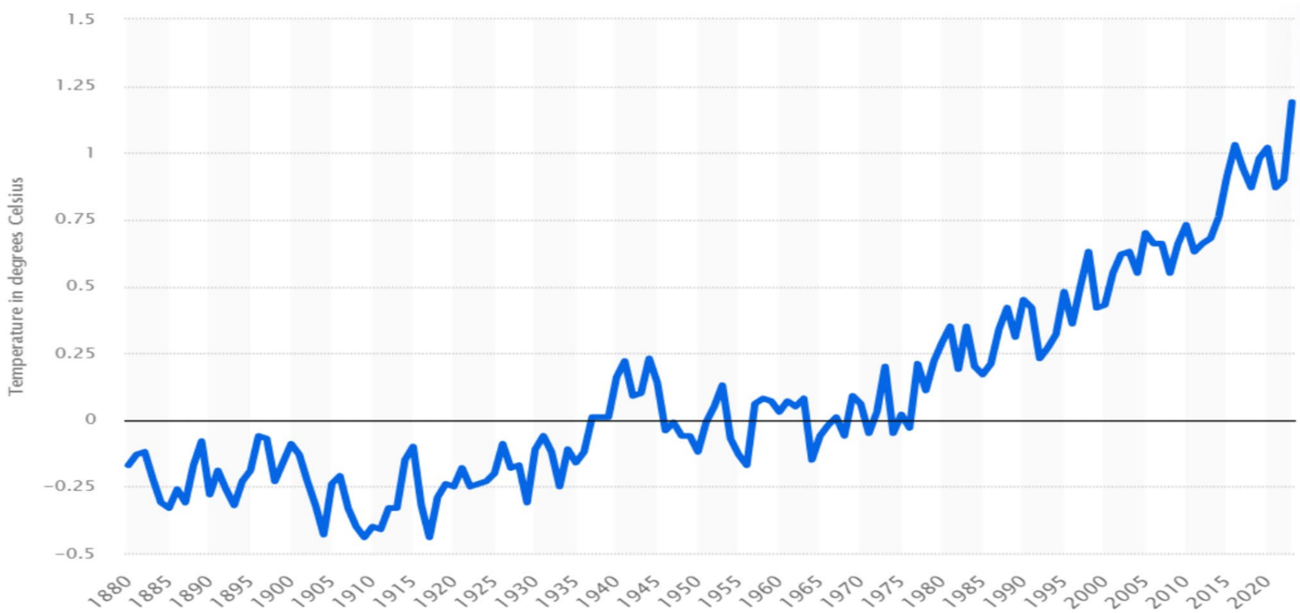

Fig. 6 Anomalies in global land surface and ocean temperatures (1880–2023) in °C. There has been a significant temperature anomaly since the 1980s, possibly due to the increasing use of natural gas in addition to oil and coal, and the significant increase in global energy consumption. In 2023, the warming anomaly of the Earth's and ocean's surface reached 1.19 °C above the twentieth-century average, the highest of the entire period. *Source*: National Oceanic and Atmospheric Administration, https://www.statista.com/statistics/224893/land-and-ocean-temperature-anomalies-based-on-temperature-departure/

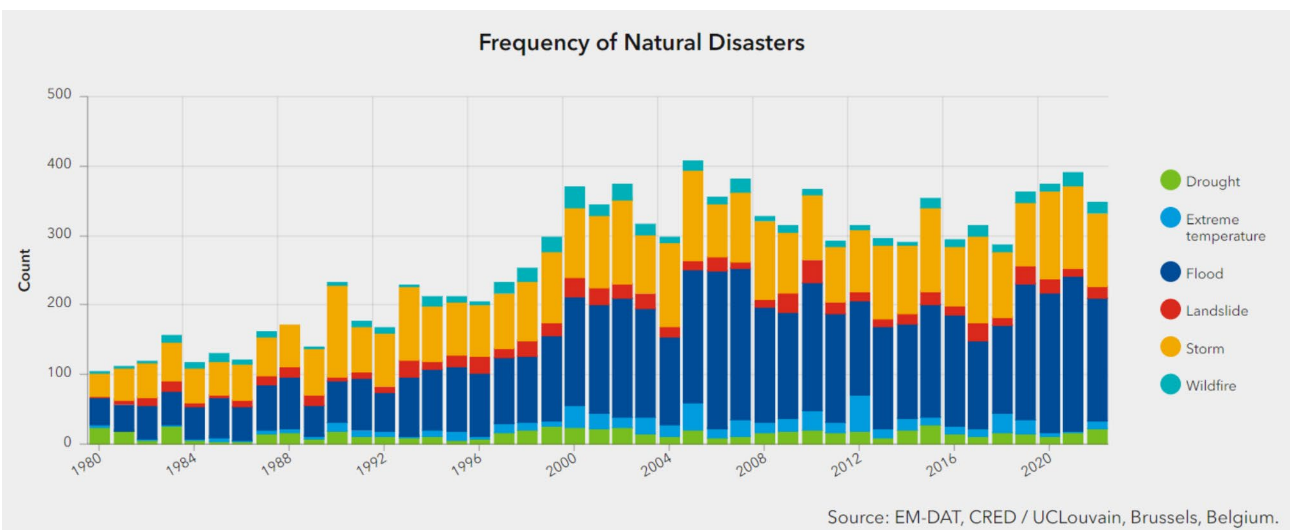

Fig. 7 Frequency of natural disasters. Following the regional perspective underlined in paragraph 1, the following figures 7. illustrate the geographical distribution of risk as they are synthesised by the International Monetary Fund. *Source* IMF: https://climatedata.imf.org/pages/adaptation#ad1

number of models recently developed; they can be grouped into three main frames.

Firstly, global climate models (*GCM*) focus on the physical processes of the main four components of climate change: the atmosphere, the oceans, the land surface and planet glaciers. They analyse the requirements for the energy balance among them; accordingly, they focus on the geographical and physical reactions to climate change of the different regions.

After the US Congress commissioned a report to analyse them (in 1983), a family of integrated assessment models (IAMs) has been developed. The goal of IAMs models is to provide a quantitative description of the interaction between human and Earth systems. They include an extremely large

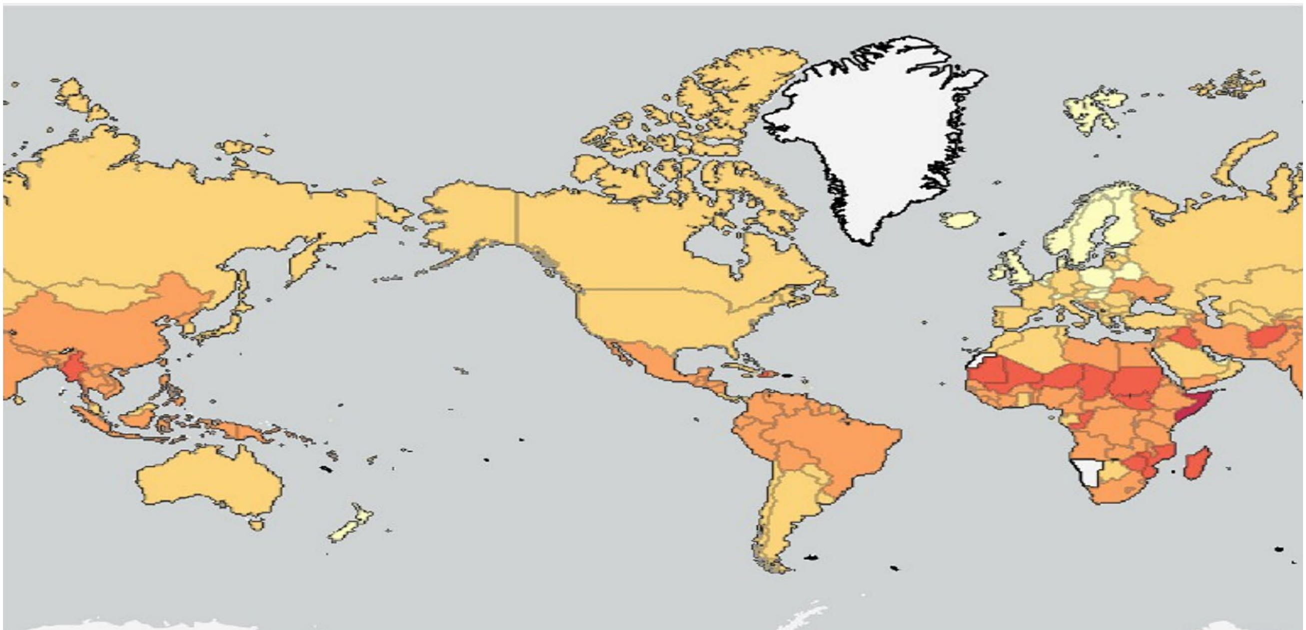

Fig. 8 INFORM RISK 2022—summary of risks estimated by the International Monetary Fund. The geographical distribution of risks is summarised in the composite index developed by the International Monetary Fund (Inform Risk, in this figure). *Source* IMF: https://climatedata.imf.org/pages/adaptation#ad1

framework of models to address the two main issues, partly from the field of physical sciences and partly from the economic discipline.

However, there is no uncertainty in the IAM models. The criticism, devastating, comes from Stern: "Aggregate models have been popular in the economics of climate change. They attempt to integrate the science of climate change, as expressed, for example, via GCMs, with economic modelling and are termed integrated assessment models, or IAMs. (…) "It is very hard to believe that models where radically different paths have to be compared, where time periods of hundreds of years must be considered, where risk and uncertainty are of the essence, and where many crucial economic, social, and scientific features are poorly understood, can be used as the main quantitative plank in a policy argument".

Thus, Stern (2008) argues, IAMs, while imposing some discipline on some aspects of the argument, risk either confusing the issues or throwing out crucial features of the problem."[39]

Furthermore, Pindick (2013), among others, states: "The models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; and the models can tell us nothing about the most important driver of the Social Cost of Carbon, the possibility of a catastrophic climate outcome. IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading." An IAM-based analysis suggests a level of knowledge and precision that is non-existent and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily. As Pindick (2013) has explained, the physical mechanisms that determine climate sensitivity involve crucial feedback loops, and the parameter values that determine the strength of those feedback loops are largely unknown. "When it comes to the impact of climate change, we know even less".

A spur to this stream of analysis, though, came from W. Nordhaus, Nobel Prize winner for the elaboration of IAM.[40] Unfortunately, Nordhaus model is rooted in the framework of neo-classical general equilibrium models, aiming at optimising climate policy through cost–benefit analysis. Coping with uncertainty is far away from his approach.[41]

[39] See also N. Stern, AER (2008). An attempt to respond to Stern criticism is in Ciarli and Savona (2019), who introduce several climate disaster-related variables into the growth model.

[40] Cf. The Dynamic Integrated Climate Economy (DICE), Nordhaus, AER 1977, n.67 pp 341–346.

[41] The main critiques to this approach focus on the impossibility of quantifying the processes and transform them into monetary costs and benefits; even the discount factor is problematic for such a very long period; finally, the application of the analysis to a "general agent" is hard to be accepted.

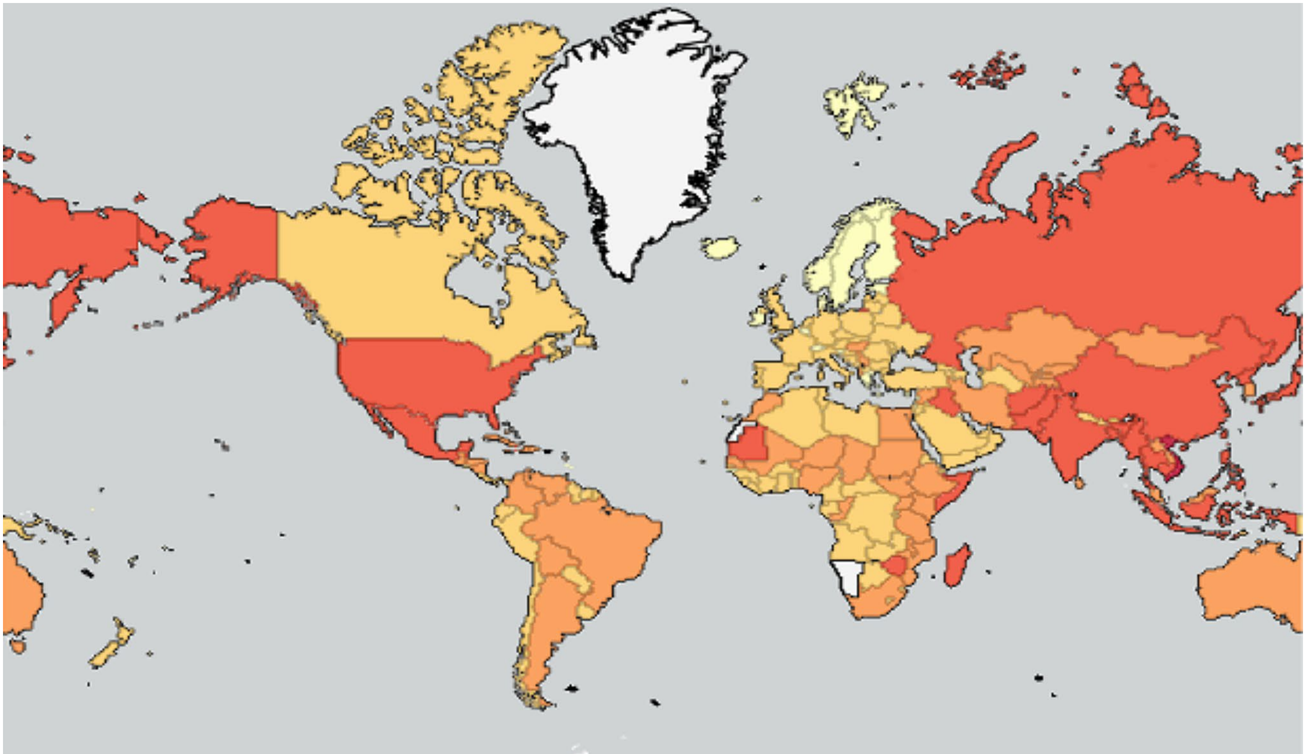

Fig. 9 Risk and exposure 2022. The vulnerability scale (this figure) highlights the heightened exposure of the poorest countries. The Notre Dame Global Adaptation Initiative has calculated that, on an annual basis, people living in the least developed countries are ten times more likely to experience a climate-related disaster than people living in rich countries. Source IMF: https://climatedata.imf.org/pages/adaptation#ad1

This has led Stern (2013) to conclude that "the climate models generally leave out many effects, recognized as potentially very large, which are not easy to make precise or formal enough for integration into the modelling. And the impact model, based on the climate models, fall far short of capturing the scale and nature of what might happen to lives and live-hoods". Thus, we can conclude with Stern that "a new generation of models is needed in all three of climate science, impact and economics with a still stronger focus on lives and live hoods, including the risks of large-scale migration and conflicts".

A second stream of models was guided by the Intergovernmental Panel on Climate Change (IPCC) and developed from the end of the'80 and during the '90's; it complemented the *cost–benefit analysis* of the economic discipline with earth, biological and physical sciences.

The criticism of these models has come from Arrow et al. (1995) who focus on the lack of property rights in analytical climate politics, again caused by the ignorance of uncertainty in those models. "Environmental damages, including loss of ecological resilience, often occur abruptly. They are frequently not reversible. But abrupt changes can seldom be anticipated from systems of signals that are typically received by decision-makers in the world today. Moreover, the signals that do exist are often not observed, or are wrongly interpreted, or are not part of the incentive structure of societies. This is due to ignorance about the dynamic effects of changes in ecosystem variables (for example thresholds, buffering capacity, and loss of resilience) and to the presence of institutional impediments, such as lack of well-defined property rights".[42]

Finally, Martin Weitzman (2009) has elaborated the "dismal theorem" to show that indefinite large expected losses derive from high-consequence, low-probability events, "under limited conditions concerning the structure of uncertainty"; he argues that: "Even just acknowledging more openly the incredible magnitude of the deep structural uncertainties that are involved in climate-change analysis and explaining better to policymakers that the artificial crispness conveyed by conventional IAM-based, CBAs here is especially and unusually misleading compared with more ordinary non-climate change CBA situations might go a long way toward elevating the level of public discourse concerning what to do about global warming."

[42] See Arrow, Bolin, Costanza (1991), Dasgupta and Maler (1995).

However, he concludes that "it is painful apparent that the dismal theorem makes economic analysis trickier and more open-ended in the presence of deep structural uncertainty. The economics of fat-tailed catastrophes raises difficult conceptual issues that cause the analysis to appear less scientifically conclusive and more contentiously subjective than what come out of an empirical CBA of more usual thin tailed situations". We can thus conclude with Ciarli and Savona (2019) that "most (if not all) aspects of structural change influence the short- and long-run relations between economic activity and the natural environment, in ways that are often not predictable, and which are not yet established in the literature".

A third stream of models[43] focuses on carbon prices to internalise the cost of polluting. However, we have seen that local carbon taxes have not beeen globally effective, cap-and-trade systems (e.g., EU Emissions Trading Systems) have not been globally effective for political and technical reasons—i.e. carbon leakage—firms produce in countries where no carbon taxes exist-, political resistance (e.g. in France), uncertainty on the future appropriate discount rate. Pacchioni (2021) proposes a different approach, focusing on the potential of transforming CO_2 emissions through a chemical process of artificial photosynthesis.

Finally, mathematicians also address the problem of interpreting the complexity of future events within the climate domain. Among others, Caravaggio and Sodini explain that they: "focus on models that in addition to giving some analytical insights into the coevolution emergence of chaotic dynamics, multi-stability and (local and global) indeterminacy." "the choice of considering the environment as productive input or as consumption good, the different hypotheses on the agents' rationality (and then the different allocative problems), and the choice between continuous and discrete time framework, have relevant consequences on the models' dynamics".[44] But from an economic perspective, they rely on neo-classical mainstream models, as they use production and utility functions that in this context are unsustainable.[58]

This brief excursus leads us to see the difficulty of using theoretical economic tools to address the effects of climatic disasters, and to define appropriate measures to prevent and adapt, from the perspectives opened up by the current economic literature on climate change.[45]

[43] Cf. M. Weitzman's criticism. In 2010 IAM models converged into the Integrated Assessment Modelling Consortium. Cf. Bosetti (2021); see also Termini (2019).

[44] The need for a long-term view in the study of climate change is argued by Marin and Mazzanti (2021) among others; see also Caravaggio and Sodini (2018).

[45] "One of the most important of ecological problems for mankind is the relationship of the quality of life for one generation with another (…). Economics cannot even dream of endling this problem", Georgescu-Roegen (1975). See also Boncinelli and Ereditato (2022).

This invites reflection in social terms: instead of a free-market model that fosters competition, a community-driven approach emphasises participation over market individualism, fostering Durkheim's notion of "social identity."

In contrast to the classical approach, which relies on the concept of collision between two entities, these entities tend to combine in a creative encounter. In this promising opposite framework, for example, the concept of defending migrants is transformed into one of demographic complementarity, in which all parties are enriched.[46] The potential of cross-cultural fertilisation between East and West also lies in its capacity for enriching interaction.[47] Theoretically that means going beyond the market, which is the second pillar of this contribution.

3.3 Beyond the market

If the market is not at the centre of economic relations, as it does happen in climate economics, prices cannot approximate the dynamics of the economy as a whole.

This brings us to the second new pillar in the organisation of economic thought: the need to move beyond the market's centrality in shaping relationships of the new millennium. The market, long considered the core of economic thought, is no longer the reliable framework for understanding and governing contemporary interactions. The so-called "virtuous" rules and mechanisms, which assume that collective welfare emerges from market competition—Hobbes's "war of all against all"—appear increasingly inadequate today. This analysis will demonstrate that only principles of sharing can effectively replace confrontation in the market.[48]

[46] On the experimentalist governance to address climate change, see Sabel and Victor (2022).

[47] Schrödinger studied Sanskrit independently to engage with the Indian Vedas.

[48] This brings us to the clear distinction drawn by Pasinetti (1964) and Hicks (1979) between the economic analyses based on production and those based on exchange relations. An extensive literature followed their analyses. I only mention here the contributions by A. Quadrio Curzio (1986) e R. Scazzieri (1993) among others who elaborated on this distinction. They introduced the crucial role of non-producible scarce resources and their interrelation with production systems and conceive different potential paths in long terms economic dynamics. In that direction they envisage the fundamental link between scarce resources and technical progress to avoid bottlenecks, that potentially offers new opportunities for economic growth. This structural vision offers the very path that could be effectively followed today, to improve the long-term economic growth reacting to the need to decarbonise the planet, thus abandoning the large contribution of fossil fuels to provide energy sources. Accordingly, they open the way to a plurality of different dynamic economic trajectories. Cfr also Quadrio Curzio et al. (2011), "Natural resource economics can be summarized by dividing it into three main lines of thought: the theory of producibility and scarcity developed by classical economists; the theory of general and natural scarcities developed by marginalists and neo-classical; the theory of dynamics with

In economics, the market is widely recognised as central to interactions between economic agents. Prices serve the function of balancing supply and demand conditions within the market. The market structure—whether competitive, oligopolistic or monopolistic—determines the degree to which prices can effectively balance supply and demand. As market structure shifts from a competitive market towards monopoly, the effectiveness of prices as a rebalancing mechanism declines. In a monopoly, prices function only to secure additional profit for the producer. Within a market—oriented production context, distinct social categories have been defined, including classes such as the proletariat, workers, industrial capitalists, rentiers, agrarian capitalists and financiers.

After decades of a neo-liberal paradigm aimed at 'liberating' the market and allowing its inherent laws to prevail, followed by a belated shift back to public responsibility for a socially and environmentally sustainable economy—amid recurrent crises—the dominant economic paradigm is now itself in crisis.

Two key issues have emerged that need to be considered separately.

1. The first issue is the reduction of the role of the market as a result of the expansion of common, collective and public goods.
2. The second issue is the undermining of social fragmentation on the one hand and the crossing of national borders on the other. Climate change is an example of this phenomenon, but by no means the only one.

The theory that positions the market at the centre of economic activity is being challenged by the rising significance of public and collective goods and the growing recognition of their essential role in sustaining life on our planet. This shift is driving greater demand for public goods, which are not traded on the market. Climate is the quintessential example of a global public good for which the market comparison proves ineffective for the goals of the planetary economy.

Complementarity of particle and waves is the second crucial concept. At the local level, this vision is exemplified by the renewable energy communities, where market price comparisons become redundant as participants generate the energy they consume. Citizen participation and behaviour become paramount to the overall outcome.

Footnote 48 (continued)

and without natural scarcities developed by macroeconomists, structuralists and empirical stylizers.". Cfr. Baranzini M, Rotondi C, Scazzieri R (2015). See also Zoboli (1996). See also R. Scazzieri (1993), Zoboli (1996).

Finally, the economies of the Western world have undergone a major transformation in recent decades with services accounting for 70%-80% of GDP in industrialized countries and the market exchange of goods shrinking to 20%. Simultaneously, radical innovations have reinforced the oligopolistic dominance of a few leading global innovators, safeguarded by intellectual property regimes that hinder upstream diffusion of these innovations, circumvent market constraints and exceed the authority of the state. This trend is particularly evident in sectors such as energy, finance, telecommunications and artificial intelligence.

These conditions have implications for the viability of using market-based instruments to implement economic policies aimed at promoting sustainable economic growth. Price-based instruments, such as global or regional carbon pricing (like ETS in UE) that spur carbon leakage and international trade tariffs, have proven ineffective.

Developing a framework of shared objectives is increasingly essential—and urgent for climate action—alongside fostering cross-cultural fertilisation to replace competitive conflicts in the global market. If the market is not at the centre of economic relations, as it is in climate economics, prices cannot approximate the dynamics of the economy as a whole. This holds even in financial processes, where uncertainty and chance reign supreme.

The climate crisis calls for economists to downgrade the importance of the law of the market, which is ubiquitous in economic theory. Rather than promoting competition, economics needs to emphasise cooperation and cultural exchange. This shift challenges the Western-centric perspective in economic analysis and the assumption of a single, predetermined path to solutions, favouring an analysis of overlapping pathways over deterministic outcomes.

3.4 Cross-fertilisation of cultures

Climate change, a global common good, cannot be effectively addressed through isolated national efforts. Yet, a foundation for global consensus remains absent. The climate crisis is forcing economists to question and reassess the importance of the law of the market which is ubiquitous in economic theory. Addressing this crisis necessitates resource and idea sharing rather than cultural conflict and confrontation.

In this context, Western-centric approaches that rely on deterministic solutions are no longer tenable. The cross-fertilisation of different realities—between East, West and the so-called "Global South"—must replace antagonism.

The impact of climatic events is driving biblical-scale population displacements as people flee environmental disasters and there is an increasing awareness of the urgent need for human action to reverse the trajectory of air pollution. This radical transformation in reality demands a new worldview of the economic discipline, distinct from that of the twentieth century.[49]

The new reference framework must take into account the fragmentation of work organisation and social roles, as well as the need for renewed public intervention beyond what the state can provide. The dominance of a few pioneering, innovative, entrepreneurs—an exclusive oligopoly—undermines genuine competition between global regions, that are strictly interconnected in the value chains of production. At the same time, growing societal fragmentation, the expansion of the service economy and migration driven by climate change, collectively call for a new economic vision.

Moreover, the ability of a few individuals, particularly innovators, to transcend national boundaries is challenging the traditional rules of the nation-state. The political and economic future remains uncertain. The economy must now adapt to a reality in which services are outpacing the production of goods and demographic shifts are becoming increasingly important.

4 Concluding remarks: keywords

We see the world as an open system where events are not predetermined. A small number of key concepts provides a guide to this vision.

The first key concept concerns the methodology used, in which the concepts of possibilities (waves of potential paths) and uncertainty—integral to the ex ante superposition of irreversible processes—are encapsulated in the first keyword.

The second key concept is that of the market. With the rising importance of public goods, especially global ones, it is increasingly clear that the market can no longer dominate economic analysis. Addressing climate risks is reconnecting humanity with nature, but not as a return to a transcendent view of divinity as the dispenser of rewards or punishments for human conduct. Rather, economics, among the social sciences, must understand and identify forms of economic growth that are also compatible with preserving the planet's natural foundations, protecting the most vulnerable populations and securing regions increasingly at risk from climate change. The climate crisis offers new opportunities for economic growth, and is a catalyst for technological innovation.

An inevitable outcome of this trajectory is the cross-fertilisation of cultural traditions. Twentieth-century economists, limited by a self-referential Western perspective, failed to recognise the potential for the hybrid integration of Eastern perspectives. Figures such as Kishore Mahbubani, the Singaporean political scientist and economist, along with Edward Said and Lee Kuan Yew—the visionary who transformed Singapore's economy in a generation—are prime examples of this.

The planet must be given its rightful place within the cosmos. Two main scientific approaches shape our relationship with nature. The first, born of the Industrial Revolution, positions humanity as the dominant force, viewing nature as a resource for human progress. The second approach, rooted in the concept of Eastern harmony, emphasises the responsibility of individuals and humanity collectively to sustain the balance of the natural world. Humanity is responsible for respecting cosmic harmony, whose rules sustain balance among all parts and cannot be breached. The cross fertilisation of these two cultural perspectives is indicative of a richness of thought, influencing and reshaping the economic dimensions of the prevailing paradigm.

It now seems both possible and necessary to make an overdue break from the determinism and market laws which provided the foundational framework for economics in the last century.

Art intuits the new phenomena, mathematics describes them. However, to understand a new reality, a coherent set of concepts is essential for interpretation. New phenomena must be observed, interpreted and governed by concepts suited to their nature. What I have tried to do here is to identify some principles that are functional today for introducing a change of vision in economics.

I will recall them:

(a) The world is an open system.
(b) The uncertainty of processes prevails.
(c) A path of different possibilities can be expressed in probabilistic waves. The strongest waves will prevail.
(d) The probabilities of these waves are not independent of each other. Everything is connected in space and time. Entanglement explains this connection.
(e) The principle of duality demonstrates that different particles (microvariables) and waves (macrovariables) are necessarily complementary, coexisting and complementing each other.
(f) Interference is creative. The meeting of two particles or events gives rise to a new reality, distinct from the sum of its parts.

[49] Concepts that have proved useful in ordering things easily acquire such authority over us that we forget their human origin and accept them as unchanging. They become 'necessities of though', 'a priori data'. The path of scientific progress then remains blocked for a long time There is no point, therefore, in analysing current concepts and pointing out the conditions on which their justification and usefulness depend. Thus their authority is shattered. And they will be replaced by others if we can develop a new system that is preferable for good reasons," A. Einstein, quoted by Bohr, (2012) p. XIII.

(g) The principle of entropy interprets the irreversible impact of radical innovations and the inexorable growth of disorder that accompanies each transformation.

We are faced with a general scientific innovation and technological applications that imply a radical change in the economy, as happened with the advent of the steam engine, electricity and the industrial revolution.

Economics, once again, stands to gain from the theoretical tools of physics. In the last century, it was classical physics—shaped by Newton and Galileo—that informed economic models. Today, principles from quantum physics might be better suited to address the inherent uncertainty of processes and change. (Majorana 1942; Majorana and Esposito 2006).

In other words, a logical dynamic describes theoretical processes which are not functions of time. Economic policy relies on these logical relations, interpreted through statistical regularities observed within a historical context. However, the outcomes of such policies cannot be simply reversed by applying symmetrical policies with opposite signifiers, contrary to the tenets of economic theory. These effects are cumulative and irreversible, even in the short term, in the interaction of subjects between different unstable equilibria.

In thermodynamic processes, entropy increases as the system moves toward a new state. Higher entropy corresponds to less information and reduced order, as is well known. Entropy never decreases; rather, state transformations proceed with increasing entropy: it implies disorder.

A change increases entropy, introducing imbalance within a system and creating an irreversible process—for example, burnt coal cannot revert to wood, nor can ash return to being a tree. Likewise, the industrial economy does not revert to an agricultural economy, nor does the service economy return to its former state. Entropy thus measures the disorder resulting from change: a tree embodies greater order than ash.

We are living in times of high entropy. The economies of the third millennium are crossing a deep transition towards a new economic world: we need a theoretical framework and tools to address this uncertainty. Some concepts introduced in this article might allow for a re-examination of the "economics of certainty". They might offer a contribution for an interdisciplinary vision of uncertain economic dynamics, as traditional economic theory increasingly struggles to interpret, even less govern, the transition of contemporary economic reality. We can conclude with Emile Durkheim that "our collective way of thinking, feeling and acting is the sense of our time."

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